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Electric power generation from solar pond using combined thermosyphon and thermoelectric modules

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Abstract

Salinity-gradient solar ponds can collect and store solar heat at temperatures up to 80 °C. As a result, these water bodies act as a renewable source of low grade heat which can be utilized for heating and power generation applications. In this paper, design and test result of the combined system of thermosyphon and thermoelectric modules (TTMs) for the generation of electricity from low grade thermal sources like solar pond is discussed. In solar ponds, temperature difference in the range 40–60 °C is available between the lower convective zone (LCZ) and the upper convective zone (UCZ) which can be applied across the hot and cold surfaces of the thermoelectric modules to make it work as a power generator. The designed system utilizes gravity assisted thermosyphon to transfer heat from the hot bottom to the cold top of the solar pond. Thermoelectric cells (TECs) are attached to the top end of the thermosyphon which lies in the UCZ thereby maintaining differential temperature across them. A laboratory scale model based on the proposed combination of thermosyphon and thermoelectric cells was fabricated and tested under the temperature differences that exist in the solar ponds. Result outcomes from the TTM prototype have indicated significant prospects of such system for power generation from low grade heat sources particularly for remote area power supply. A potential advantage of such a system is its ability to continue to provide useful power output at night time or on cloudy days because of the thermal storage capability of the solar pond.

Keywords: Thermosyphon; Thermoelectric generator; Solar pond; Power generation; Renewable energy

1. Introduction

Salinity gradient solar ponds are large bodies of water that act as solar collectors and heat storages. Solar pond is a simple and low cost solar energy system which collects solar radiation and stores it as thermal energy for a relative longer period of time. When solar radiation penetrates through the solar pond surface, the infrared radiation component is first absorbed in the surface mixed layer or upper convective zone. However, this heat is lost to the atmosphere through convection and radiation. The remaining radiation will subsequently be absorbed in the non-convective zone and lower convective zone before the last of the radiation reaches the bottom of the pond. In these ponds, the solution is heavier in the lower region because of higher salt concentration. As a result, the natural convection that takes place in normal ponds is suppressed. Solar radiation penetrating to the bottom region is thus absorbed there, and temperature of this region rises substantially since there is no heat loss due to convection. The temperature difference created between the top and the bottom of the solar ponds can be as high as 50–60 °C. The collected and stored heat can be extracted and used for industrial process heat, space heating, and even power generation (Akbarzadeh et al., 2005).

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Nomenclature

I	current (A)
k	thermal conductivity (W/m·K)
P	electrical power (W)
$\dot{Q}$	heat transfer (W)
ρ	electrical resistivity (Ω·m)
ER	electrical resistance (Ω)
T	temperature (°C)
R	thermal resistance (K/W)
ΔT	temperature difference (°C)
α	Seebeck coefficient (V/K)
Z	figure of merit (K^{-1})

Subscript

cs	cold side
eff	effective
ex	external
hs	hot side
oa	overall
t	total
TEG	thermoelectric generator

A typical solar pond consists of three regions, the upper convective zone (UCZ), the non-convective zone (NCZ) and the lower convective zone (LCZ) as shown in Fig. 1. The upper convective zone is the topmost layer of the solar pond. It is a relatively thin layer that consist almost fresh water. The non-convective zone is just below the upper convective zone and has an increasing concentration gradient with respect to the pond depth and relative to the upper convective zone. It also acts as thermal insulation for the bottom layer. The LCZ has highest salt concentration without any salinity gradient. In solar ponds, if the concentration gradient of the NCZ is great enough, no convective current will occur in this region, and the energy absorbed in the bottom of the pond will be stored in the LCZ.

Extensive research has been carried out to utilize the thermal energy produced by solar ponds to produce electric power (Tabor and Doron, 1986). The best showcase for such power generation was the project near the Dead Sea in Israel where 5 MW electric power was produced using a Rankin Cycle heat engine from a 210,000 m^2 salinity-gradient solar pond having a depth of 4.5 m (Ha, 1984). Although generation of electricity from large solar ponds has been successfully demonstrated, for power generation from small scale solar ponds there has not yet been a practical and viable proposal. A solar pond does not have to be larger than a few hundred square meters to be able to produce enough heat that after conversion can satisfy the electricity demand for an energy-efficient house (say 2–5 kW h/day). While construction and maintenance of a solar pond of this size is not a problem, the conversion of thermal energy to power is a difficult challenge. Conventional heat engines have too many moving parts and are complex. They are very expensive (15,000–20,000 $/kW) in these small sizes (less than 0.5 kW for the above example) and difficult to maintain.

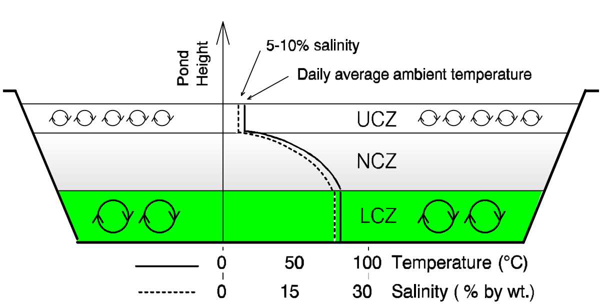

Fig. 1. Salinity-gradient solar pond.

In the present research it is shown that by combining thermosyphons and thermoelectric cells, it would be possible to utilize the temperature difference existing between the top and the bottom of a solar pond and produce electric power in a fully passive way, i.e. no moving parts. In such a scheme, the heat is transferred by the thermosyphon from the lower region of the pond to the 'hot' side of thermoelectric cells which maintains a good thermal contact with the top of the thermosyphon tube. The 'cold' sides of the cells are in contact with the cold environment of the top layer of the solar pond.

The above proposal utilizes thermosyphons, which are highly effective devices for heat transfer (Dunn and Reay, 1994; Esen and Esen, 2005; Chen et al., 1983; Tundee et al., 2010; Imura et al., 2005), and thermoelectric cells, which can effectively convert a temperature difference to electric potential and generate power (Rowe, 1995; Chen et al., 2002; Rowe and Min, 1998; Wu, 1996; Nuwayhid et al., 2005; Riffat and Ma, 2003). Both of these devices do not have any macro scale moving parts and are thus fully passive. Although at present, the efficiency of conversion of heat to electricity by thermoelectric cells is still low (2% for a 50 °C temperature difference) and at its best is 10–20% of the Carnot efficiency for the same temperature difference, the availability of the cells and their simplicity suggest that these devices may be very suitable candidates as small and simple energy converters in applications such as small solar ponds. Of course the developments in recent years in semiconductor materials for thermoelectric cells and the resultant improvements in their efficiency are promising indications that these cells have good potential to be economically viable candidates for conversion of low grade heat (produced in most solar collectors) into electricity. It should be noted here that the technology for the manufacture of thermosyphons for application such as above is fully developed (Faghri, 1995) and thermosyphons of different sizes can be easily manufactured requiring only a moderate amount of skill.

2. Theory

2.1. Thermosyphon

The gravity assisted thermosyphon is an effective heat transfer device that utilises latent heat of the working fluid, flowing under the influence of gravity, to transport heat from the source to the sink. As the latent heat of vaporization is relatively high, the thermosyphons can transfer large quantity of heat with very small end to end temperature differential and thus low thermal resistance. In the thermal analysis of the gravity assisted thermosyphon correlations from ESDU (Engineering Data Science unit No. 81038, 1983) were used. The total thermal resistance (R_t) from heat source to the heat sink for thermosyphon is related to the actual overall heat transfer ($\dot{Q}_{oa}$) as below:

$$\dot{Q}_{oa} = \frac{\Delta T_{eff}}{R_t} \tag{1}$$

where, ΔT_{eff} is effective temperature difference between heat source and heat sink.

2.2. Thermoelectric generator

In remote areas, where the electric grid is not available and the sun shines year round, combined power generation modules based on the small scale solar pond, thermosyphon and thermoelectric cells is one of the viable candidates for providing daily electricity demand. A TEC has the advantage that it can operate from a low grade heat source such as waste heat energy. It is also attractive as a mean of converting solar energy into electricity. The schematic diagram of the single thermoelectric element is shown in Fig. 2. It consists of two dissimilar materials, n-type and p-type semiconductors, connected electrically in series and thermally in parallel. Number of these thermoelectric elements are combined in series to form a thermoelectric generator module.

Heat is supplied at hot side of the thermoelectric cell while the other end is maintained at a lower temperature by a heat sink. As a result of the temperature difference,

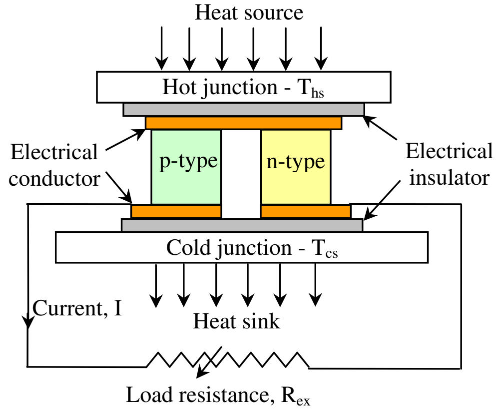

Fig. 2. Schematic diagram of the thermoelectric element.

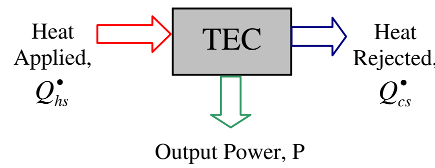

Fig. 3. Schematic showing the energy flow in the TEG.

Seebeck voltage is generated across the p-n junction that results in current flow through an external load resistance. The power output depends on the temperature difference, the properties of the semiconductor materials and the external load resistance. Desirable properties for the thermoelectric material as a generator module are expressed by its figure of merit (Z) which is defined as:

$$Z = \frac{\alpha^2}{\rho k} \tag{2}$$

where, α is the Seebeck coefficient of the p-n junction, ρ is the electrical resistivity and k is the thermal conductivity of the thermoelectric element. Figure of merit can be expressed in non-dimensional form as ZT, in order to take the effect of the temperature on material properties. Here, T is the temperature of the TEC hot side.

Fig. 3 shows the energy flow through the thermoelectric cell where P represents the useful electric power output by the TEC. Each thermoelectric element is assumed to be insulated, both electrically and thermally, from its surroundings, except at the junction to hot/cold reservoir contacts. The internal irreversibility for the TEC is caused by joule electrical resistive loss and heat conduction loss through semiconductors between the hot and cold junctions. The external irreversibility is caused by finite rate heat transfers at the source and the sink.

3. Proposed system

3.1. Description

The schematic of the proposed power generation unit is shown in Fig. 4. Here a thermosyphon, which is basically an evacuated copper tube charged with water as the working fluid, is held vertically and is long enough to connect the bottom convective zone of the pond to the top convective zone. The proper cleaning of the thermocouple components before assembling was performed as well as degassed and distilled working fluid was used to avoid any non-condensable gases formation. During the experimentation, the readings from different thermocouples installed on the condenser section were used to detect any non-condensable gas formation. In case of non-condensable gas generation, the thermocouples will show different output temperatures for the condenser section which otherwise should be relatively isothermal. In the set-up, a vacuum pump was also connected to the thermosyphon to remove any detected non-condensable gas. In Fig. 4, a typical temperature profile for a solar pond is also given. It is seen from this profile

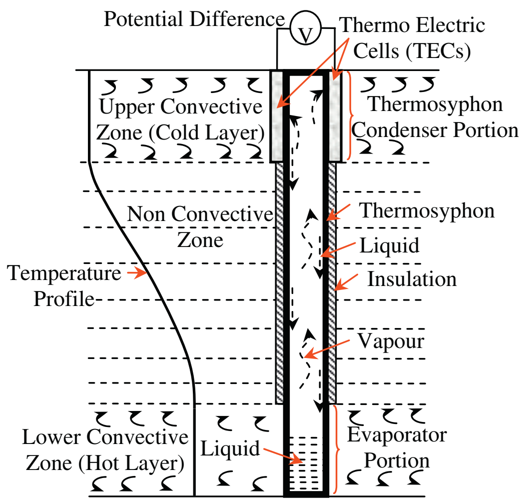

Fig. 4. Schematic showing the concept of generating electric power from salinity-gradient solar pond using a combination of thermosyphon and thermoelectric cells.

that the temperature is low and uniform in the top zone. This uniformity is caused by the wind induced wave actions near the top. In this zone, the temperature follows closely the daily average ambient temperature. In the middle layer of the pond, where the convective currents are suppressed because of the existence of a strong salinity gradient, the temperature rises continuously until it reaches a maximum near the interface with the lower layer. In the bottom layer the temperature is also uniform as in the top layer. The mixing in the bottom zone is primarily due to the absorption of solar radiation by the dark bottom of the pond, and the convection currents that are thereby induced. Therefore the non-convecting middle layer, which is sometimes called the gradient layer, separates the upper zone (cold) and the bottom zone (hot). Some typical thicknesses for these three layers are: 0.2–0.6 m for the top layer, 1–2 m for the middle layer, and 0.5–5 m for the bottom layer.

The middle section of the thermosyphon (adiabatic section) is insulated to prevent heat losses from the thermosyphon to the surrounding water in the gradient layer, which is at a lower temperature than the bottom layer. The thermoelectric cells are attached to the top part of the thermosyphon (condenser section) with a good thermal bond. The other side of the cells is cooled by the cold and convective currents available in the top convective zone. Therefore the required temperature difference for power generation is created on the two sides of the thermoelectric cells. Fig. 5a shows the picture of the salinity-gradient solar pond (8 m in diameter and 2 m deep) located at RMIT University that will be used to test the proposed thermosyphon TEC module. In Fig. 5b and c, the density and temperature profile for the solar pond is given.

3.2. Working

The working fluid is continuously evaporated in the evaporator and the resulting vapor travels upward because of the lower pressure in the condenser section caused by a lower temperature. The vapor is then condensed releasing its latent heat, which is transferred to the sides of the thermoelectric cells attached to the thermosyphon. The resulting condensate travels downward because of gravity. As a

Fig. 5a. Salinity-gradient solar pond located at RMIT University, Australia.

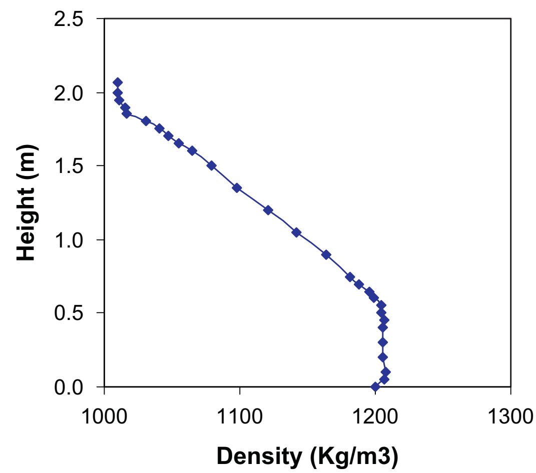

Fig. 5b. Density profile of the salinity gradient solar pond located at RMIT University for summer season.

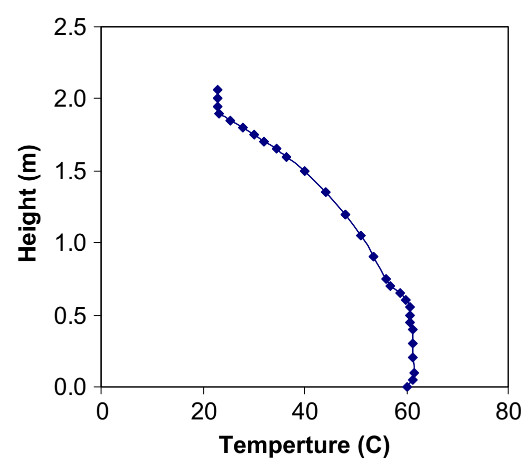

Fig. 5c. Temperature profile of the salinity gradient solar pond located at RMIT University for summer season.

result the two sides of the cells are maintained at different temperatures, and hence an electric potential difference is generated across the cells. On applying an external electric load, an electric current is produced and electric power generated. The produced electric power can be directly used for applications requiring direct current, or converted into alternating current if needed. The electric energy thus produced can be also continuously stored in batteries to provide power to intermittent loads, which may have a higher demand than the capacity of the thermoelectric cells for a period of time.

4. Laboratory testing and results

In order to test the viability of the proposed system of power generation, some preliminary tests were performed. Suitable thermoelectric cells that can be used for power generation were obtained from Kryotherm Ltd., Russia. These cells are 40 mm by 40 mm and have a thickness of 3.9 mm. Sixteen TECs were individually tested by subjecting them to temperature differences by heating one side and cooling the opposite side. These tests helped to qualify the output and performance of each module. The tested modules were installed on the condenser of the lab scale thermosyphon to form a single TTM prototype. Temperature was measured using T-type thermocouples with an accuracy of ±0.5 °C. The maximum error in the measurement of current using ammeter was ±0.01 A and voltage using voltmeter was ±0.01 V. The error in the calculation of the power output from TEC was higher at smaller temperature difference across the cells due to smaller output power. Such lower temperature difference occurs at the lower operating temperatures of the TTM system. The maximum error in the calculation of temperature difference across TEC and output power from the thermoelectric generator was ±10.4% and ±25% that arises at 50 °C operating point. For higher operating temperatures, error in ΔT and output power was below ±5.6% and ±10% respectively. The test set-up for testing the individual TEC is shown in Fig. 6.

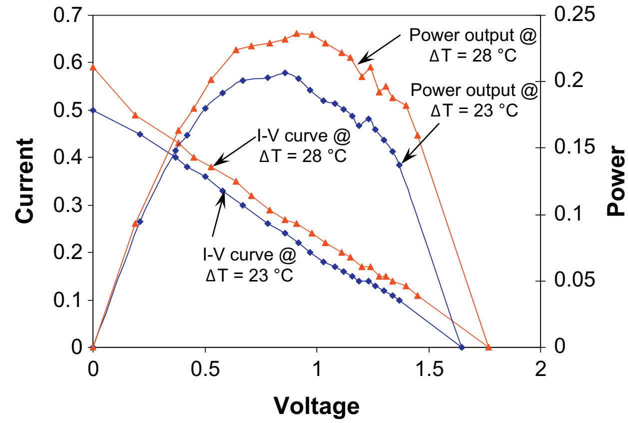

Fig. 7. Tests assembly to simulate the operation of the combined thermosyphon and thermoelectric cell under solar pond conditions.

As shown in Fig. 6, the heat load simulator comprising of a copper block with the cartridge heater inserts was used to heat one side of the thermoelectric cell while liquid heat sink with water flow arrangement was used to remove the waste heat from the opposite cold side of the TEC. Fig. 7 presents the results for two thermoelectric generators. Attempts were made to produce experimental conditions similar to the solar pond. It was shown that for a temperature difference of 28 °C, TEC can produce open-circuit voltage of 1.77 V, short circuit current of 0.59 A and maximum power of 0.24 W. With the decrease in the

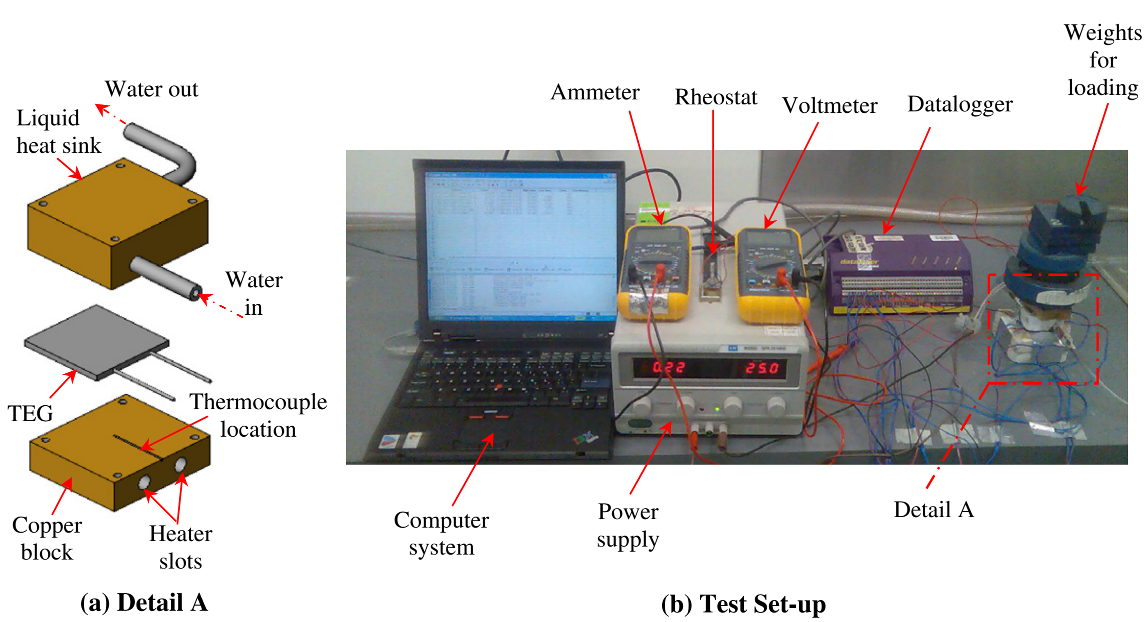

Fig. 6. Experimental facility showing details of set-up used to test the performance of TEC.

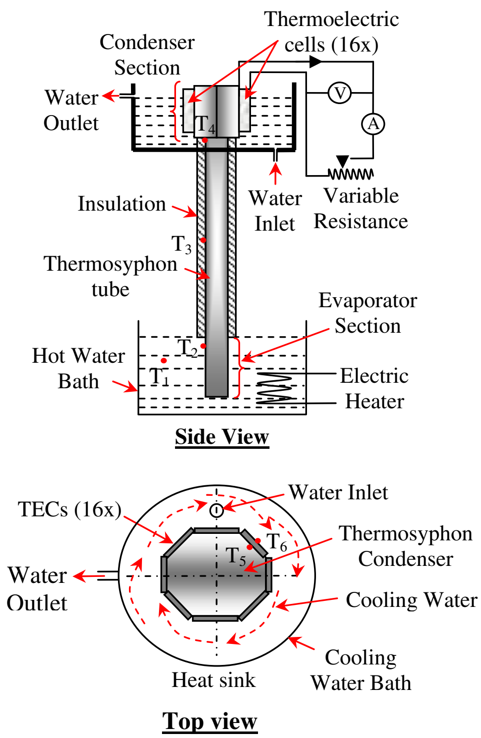

Fig. 8a. Tests assembly to simulate the operation of the combined thermosyphon and thermoelectric cell under solar pond conditions.

temperature difference to 23 °C, the maximum power drops to 0.21 W.

Indoor laboratory tests were also carried out on a combined system of thermosyphon and thermoelectric cells to simulate the operation of the system when installed in the solar pond. For this purpose a thermosyphon was made from a 100 mm diameter copper tube with a total length of 2 m. The thermosyphon was charged with water as the working fluid. The schematic of the prototype and the test rig is shown in Fig. 8a–d. As seen in the Fig. 8a and c, the sixteen thermoelectric cells, which are connected in series,

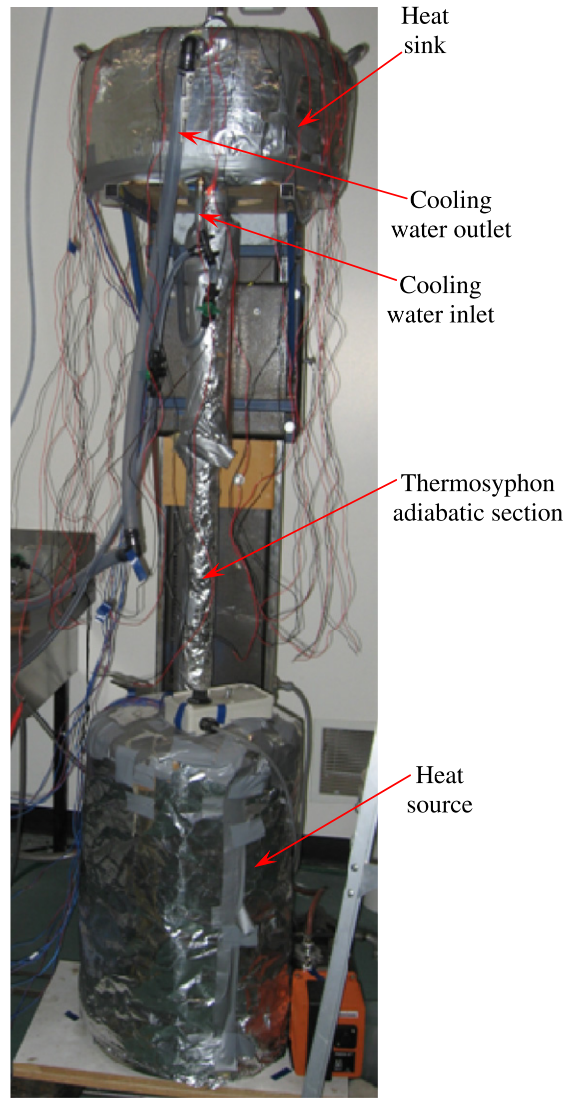

Fig. 8b. Combined thermosyphon and thermoelectric modules test rig.

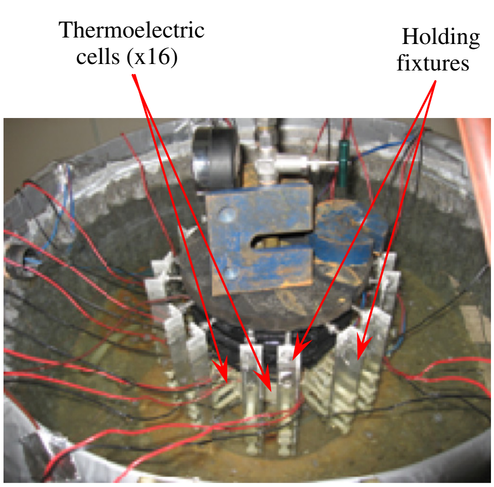

Fig. 8c. Condenser section of the combined TTM rig showing the TEC and attachment fixtures.

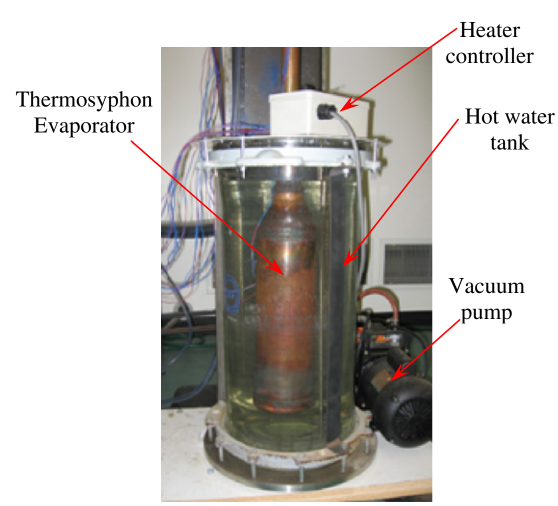

Fig. 8d. Evaporator section of the combined TTM rig with the heating arrangement.

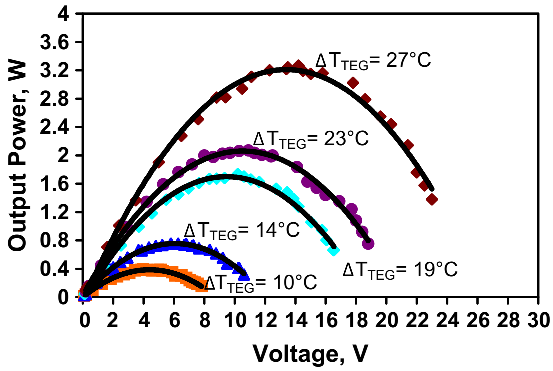

Fig. 9. Dependence of output power on ΔT across TEG and external resistive load.

are attached to the top part of the thermosyphon. This is the part that will be in the top convective zone of the solar pond which is the heat sink. As shown in the Fig. 8a, b and d, the lower section is heated by a hot water reservoir fitted with electric immersion heater. This results in the heating of the inner side of the thermoelectric cells through the thermosyphon. The outer sides of the cells are cooled by flowing water that simulates the cooling effect of the top layer of the solar pond.

Fig. 9 shows the test results on the Thermosyphon Thermoelectric Module (TTM) for different heat source temperature (i.e. hot water bath temperature, T_1). On the figure, the temperature difference achieved across the TEC (ΔT_{TEG}) when the water bath temperature is changed from 50 to 90 °C is mentioned (with the top curve corresponding to the 90 °C). It can be seen from the graph that the power generated by the TTM module increase with the increase in the temperature across TEC which tracks the increase in the temperature of the hot water bath. Here, the temperature of the hot water bath simulates the temperature of the bottom dense layer of the solar pond. For each setting of evaporator temperature (T_2), the maximum power point for the TTM system was achieved by changing the external resistance (or load). For evaporator surface temperature of 90 °C, maximum power of 3.2 W was generated by the TEC units. It should be noted that the temperature across the TEC does not increase in the same proportion as the water bath temperature due to the limited cooling on the cold side of the TEC.

Fig. 10 shows the *I–V* characteristics of the TEC units for hot water bath temperature of 90 °C and temperature difference of 27 °C cross thermoelectric generator. In this case, the open-circuit voltage and the short circuit current values of 26 V and 0.4 A respectively were obtained. As seen from Fig. 10, the power curve is parabolic in shape with maximum power point of 3.2 W obtained at 13.4 V and 0.24 A. In contrast to photovoltaic cell, the maximum power point of the thermoelectric module is always obtained at half the open-circuit voltage due to the linear *I–V* characteristics. This emphasises the importance of internal resistance in determining the performance of thermoelectric device. In Figs. 9 and 10, the solid lines represent the trend lines fitted to the experimentally obtained data.

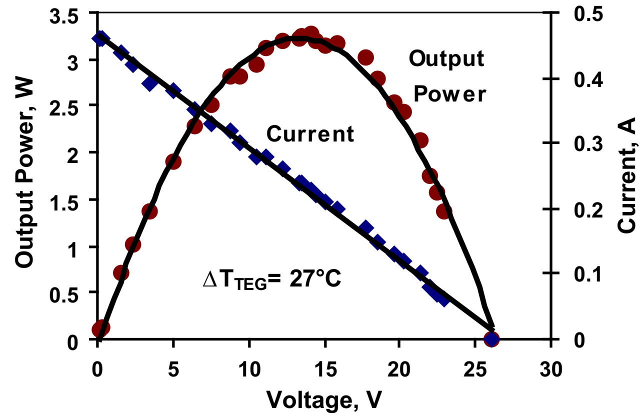

Fig. 10. *I–V* Characteristics and power output for 90 °C hot bath temperature and 27 °C ΔT across TEG respectively.

Attempts are made to utilize the existing data available for off-the-shelf thermoelectric cells and design a thermosyphon-heated thermoelectric module (TTM) that can be used as a building block for power generation from salinity-gradient solar ponds. For this purpose use is made of the commercially available cells such as TGH-199–1.4–0.8 produced by Kryotherm. These cells are 40 mm by 40 mm and have a thickness of 3.9 mm. According to the manufacturer each of these cells can produce 3.2 W at a voltage of 2.6 V if the cold side is maintained at 50 °C and the hot side at 150 °C. The stated efficiency for these conditions is 3.8%. Under solar pond conditions the efficiency would be lower than this. By using a number of the above cells in series, as investigated in the lab experiment, one would be able to design a TTM suitable for battery charging (12 V) using the heat from the bottom of the solar pond. The output power of the unit can be designed between 10 to 20 W under normal conditions of the pond by choosing appropriate number of thermoelectric cells. The rate of heat transfer through each TTM is estimated to be about 1 kW for a 10 W unit; that is, the energy efficiency of the conversion is around 1%. A number of the above TTMs can form the power supply system for a small house. For example for a small energy-efficient house, the needed electrical energy can be as low as 2 kW h/day. Since the TTM works day and night then a total number of 10 units would be required to power the house. It should be noted that a suitable coating needs to be applied to the TTM to protect the device against the salt environment.

5. Conclusions

The following conclusions can be derived from this study:

- It has been shown that by combining thermosyphon and thermoelectric cells it is possible to produce a fully passive and simple power supply system for remote area applications using the temperature differences that exists in a typical solar pond.

- Lab scale test prototype was designed for the proof of concept. The designed power generation module consisted of copper-water thermosyphon, 100 mm in diameter and 2 m in length, and 16 thermoelectric cells, each 40 mm by 40 mm and 3.9 mm thick, installed on the external surface of the thermosyphon condenser.
- The designed TTM module was able to provide maximum power of 3.2 W which was obtained at 13.4 V and 0.24 A when the temperature difference of 27 °C was maintained across 16 thermoelectric cells. In this case, the open-circuit voltage and the short circuit current values of 26 V and 0.4 A respectively were obtained.
- The proposed thermosyphon – thermoelectric module will be most suitable for small-scale applications of solar ponds for power generation.
- The thermosyphon-heated thermoelectric module is easy to manufacture and mostly uses off-the-shelf components.

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